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Evaluating Robot-Operator Job Performance

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PREFACE

This document was prepared under a task titled "Critical Technology Issues for the Future Combat Systems Command and Control" for the Tactical Technology Office, Defense Advanced Research Projects Agency. The project leader was Peter S. Brooks, succeeded by Franklin L. Moses at the Institute for Defense Analyses.

CONTENTS

FIGURES

TABLES

EXECUTIVE SUMMARY

BACKGROUND

Assessments of small air and ground robot systems often focus on how well the equipment functions. Those assessments also should include the human operator and how well the robot and operator work together as an integrated system. Tests that do include performance of the human operator often rely on qualitative observations—observer judgments and interviews about workload, situation awareness, cognitive issues, and so on. This paper views the operator and robot as a team, outlines a schema for measuring robot-operator team performance, and presents an initial proof-of-principle test for quantitatively assessing that performance.

The initial proof-of-principle test (1) defined robot-operator performance factors associated with moving a small robot from point A to point B and (2) quantified the effects that different sensor and navigation technologies have on that performance.

METHODOLOGY

The proof-of-principle approach was to instrument the robot and the operator interface to allow measures of operational performance in navigation-reconnaissance tasks. The instrumentation enabled measurement of efficiency and effectiveness (e.g., frequency of control actions, time between control actions) and errors and accuracy. These kinds of measurements provide data about mission performance contributions spanning robot capabilities, operator skills, employment strategy, interface limitations, and so on.

System Components

A team consisted of a single operator and robot. An experimenter/observer ran the tests. The robot was equipped for operator control using teleoperation via Ethernet or for operator control with the help of electronic navigation aids.

The operator's workstation had a laptop to provide a control display with four information areas: (1) map, including robot position and activity; (2) error feedback window; (3) live-camera video, and (4) quick-reference command list showing all

operator-robot inputs. The map on the laptop's display showed the test course of approximately 135 × 95 feet in a level-floor parking garage. The test course consisted of gates and obstacles for the robot-operator team to navigate through and around. Operator control of the robot was done using the laptop's keyboard and mouse.

Procedure

An observer showed and explained the robot and its features to the operator. The observer also showed and explained a training course and its features but not the test course.

There were two different navigation conditions: unaided and aided. Without electronic navigation (unaided), the operator performed all control via teleoperation, the most common way to operate robots today. With electronic navigation and teamwork (aided), the robot assisted the operator in navigating a route in two ways: (1) it followed a sequence of operator-selected waypoints, and (2) it avoided 3D objects. The navigation task for both conditions was to drive the robot through a series of numbered gates while avoiding obstacles.

RESULTS AND DISCUSSION

Analyses compared individual operator performance under aided and unaided conditions for each test run. Control actions—the number of key presses as well as the mean times and ranges of times between key presses—were calculated. Error frequency also was compiled. Table ES-1 gives the results of this comparison. Compared with unaided navigation, aided navigation had fewer control actions, more free time (intervals of greater than 5 seconds between control actions), but a higher number of errors.

Table ES-1. Mean Number and Mean Time for Response Parameters

Navigation	Number of Key Presses	Free Time / Navigation	Number of Errors
Aided	12	7.8 s	>1
Unaided	50	1.6 s	<1

Less operator attention and interaction with the robot generally seems to equate with more errors, suggesting that operator vigilance needs emphasis or that the navigation technology needs enhancement for improved performance.

CONCLUSION

The test demonstrated the usefulness of evaluating robot-operator teams to assess success and failure factors in the performance of robots and the effects of different technologies on that performance.

RECOMMENDATIONS

The measurement concept developed and tested as a proof of principle would benefit from additional assessment and enhancements before transition to the user community. The next steps should be to extend the measurement approach to more complex robot-operator tasks with the goal of providing quantified answers to which technologies will help robot-operator teams better accomplish their jobs. The current work with one type of robot and limited data needs expansion to show that the concept generalizes. Additional tests should include data logs and metrics for other ground robots and for air robots. To make implementation easy, the schema and instrumentation for data collection need to be relatively compatible with different onboard computers, data-logging systems, and user interfaces and control stations of various robots. The most effective way for that to happen is for contractors and developers to integrate the evaluation methodology into their robot systems and planning for employment under more realistic conditions than in the current study.

I. INTRODUCTION AND PURPOSE

The effectiveness of a system generally is determined by how well it performs a mission or task. To improve a system, developers must examine individual components and assess their contribution to overall system performance. Assessments of small air and ground robot subsystems often focus on how well the equipment functions. However, those assessments should also consider the human operator subsystem and how well the operator and robot components work together as an integrated system.

An Army Science Board assessment of robot-operator interface issues concluded that robotic associated technologies themselves are not the major issues in robot system performance. Instead, frequent shortfalls include:

- Robot-operator interfaces are ad hoc, developed primarily by engineers for engineers, and not systematically evaluated.
- No rigorous efforts exist to understand robot mission functions, robot limitations, and the consequent operator interactions.
- No metrics exist for systematically improving operator-robot interactions.

In addition, tests that do include performance of the human operator often rely on qualitative observations—observer judgments and interviews about workload, situation awareness, cognitive issues, and so on. They lack quantitative measures related to total system performance. To emphasize the total system, this paper views the operator and robot as a team. It outlines a performance schema for that team, presents an initial proof-of-principle test for quantitatively assessing the team's performance, and interprets data from the test.

The initial proof-of-principle test (1) defines (robot-operator) performance factors associated with moving small robots from point A to B and (2) quantifies the effects that different sensor and navigation technologies have on that performance. Measures were designed to be as non-task and non-platform specific as possible so that generalizations could be made.

The proof-of-principle approach was to instrument the robot and the operator interface to allow measures of operational performance in navigation-reconnaissance tasks. The instrumentation enabled measurement of efficiency and effectiveness (e.g.,

frequency of control actions, time between control actions) and errors and accuracy. These kinds of measurements provided data about mission performance contributions spanning robot capabilities, operator skills, employment strategy, interface limitations, and so on. The payoff is that program managers and developers can use measurement schema like the one described to help diagnose and improve robot-operator team configurations and to assist in technology trade-off and investment decisions.

II. BACKGROUND

A. ROBOT–OPERATOR TEAMWORK

This project approached the development of measures from the perspective of robot-operator teams and the effectiveness and efficiency of their teamwork. In one of the most widely cited working definitions of a team, Salas et al. (1992) characterized a team as having a function, goal, and direction:

> …a distinguishable set of two or more people who interact, dynamically, interdependently, and adaptively toward a common and valued goal/objective/mission, who have been assigned specific roles or functions to perform, and who have a limited life-span of membership [p. 4].

This definition suggests that each team member has a specific role representing a critical contribution to effective system performance. In the robot-operator team, each partner has distinct tasks and unique responsibilities: the operator plans, directs, and monitors the robot, while the robot uses its sensory and surveillance capabilities to investigate environments separate from the operator. The robot and the operator each have responsibility for different aspects of performance, but they are dependent on one another to complete missions. Measurement, therefore, must account for how effectively and efficiently they each perform independent tasks and share dependent requirements. The load on the operator during an operation varies according to: (1) the number of interdependent and entirely operator-directed actions required and (2) the features of the robot that supplement or take over some operator functions. One day, robots may be designed to be more acutely sensitive than operators to environmental cues that can have critical informative impact on operator decision-making.

Interdependence represents a key parameter of teams. Members coordinate their activities, either sequentially or simultaneously. In robot-operator teams, the mission typically is initiated by the operator; however, during the mission, the actions and reactions of the operator become dependent upon actions and information from the robot. Thus, robot-operator activity reflects a high level of interdependence.

Further, the robot-operator team is designed for particular types of missions, typically involving the robot's entry into and operation within dangerous environments, as directed by the operator.

The definition and designation of the robot-operator system as a team sets the foundation for a measurement system. Most team-performance models define effectiveness as a function of team processes or of the interactions among team members. Likewise, Brannick and Prince (1997) argued, "a comprehensive measure of team performance needs to contain elements of both process and outcome" (p. 10). Accordingly, performance measures that can apply to robot-operator teams reflect both the electronic-based interactions between operator and robot (e.g., operator keystrokes) and indices of mission outcomes (e.g., mission accomplishment; time to completion, and error rates). A central task in this effort was to specify particular processes for the robot-operator team environment and to define behavior-based indicators of these processes.

B. TEAMWORK ASSESSMENT

Two types of functions, planning and coordination, abstracted from Marks et al. (2001), are particularly critical for effective team performance. Planning occurs before and in anticipation of team action, while coordination is essential to actions for carrying out the plans. Operators make the higher order planning decisions, while robots provide information crucial to overall task planning, as well as to the adaptation and recalibration of plans during team actions.

Coordination functions include the simultaneous synchronization of actions by the robot and the operator. These functions require feedback and monitoring of team activities, error detection and correction, and backup behaviors, where one team member can provide corrective information to another and assist in performance. Coordination represents an essential component of processes in robot-operator teams.

The assessment of robot-operator team performance necessarily rests on

(1) Behavior-based indices of processes (e.g., latency of responses to encountered obstacles)

(2) Markers of electronic communications (e.g., frequency and pattern of operator signals to the robot, frequency and pattern of robot signals to the operator)

(3) Outcomes of collaborative activity (e.g., mission accomplishment, time to mission accomplishment, aggregated accuracy and error rates)

Table 1 lists indicators of team processes for robot-operator performance. This table also provides examples of how these processes can be measured for the navigation-reconnaissance tasks used in the current project.

Table 1. Robot-Operator Team Performance Measures

Robot-Operator Team Processes and Performance	Measurement Indicators
Information exchanges about task situation	Frequency and timing of electronic exchanges (e.g., operator control actions anticipating obstacles or robot alerts about environmental obstacles and events)
Directive information (planning-into-action)	Operator control actions and patterns (e.g., time actually spent controlling the robot)
Monitoring and feedback regarding goal-path adherence	Alerts and warnings by the robot to the operator and frequency of queries by the operator to the robot
Activity monitoring and backup behaviors	Frequency of operator interventions to correct robot course after encounters with obstacles and blockages Frequency of course adjustments made by operator Frequency of robot alerts following operator keystrokes
Coordinated (sequential, simultaneous, integrated) actions by operator and robot	Aggregated latency between keystrokes and robot signals Latency of operator corrective responses to robot Frequency of robot “freezes” (i.e., robot backed into part of maze and cannot move out)
Pacing of team activity	Time to sub-goal completion Frequency and timing of electronic exchanges throughout mission
Team performance	Mission accomplishment Time to mission accomplishment Percentage of task requirements met Aggregated accuracy and error rates (errors include frequencies of 2D obstacles crossed by robot, 3D obstacles hit by robot, misidentification of environmental threats and events)

The robot-operator team performance measures developed in this effort were selected for their sensitivity to the cognitive load requirements on the operator. The operator depends on teamwork with the robot to reduce the amount of cognitive effort needed to control it. The most efficient and effective robot-operator team performance occurs when the operator can minimize both cognitive resource allocation to, and intervention in, robot activities once a team mission and plan is set in motion. In such instances, the operator's cognitive resources can be directed toward broader strategic and team-management issues.

The proof-of-principle test described in the next section of this report was designed to assess the impact of robot technologies on teamwork performance. The implications for cognitive load reduction of different robot technologies vary. This study applies the robot-operator team performance measures to assess the impact of one technology feature, robot-aided navigation, which can have significant effects (both positive and negative) on operator cognitive load. This feature, while not widely used effectively in most applied robot settings, allows for a valid test of the proposed measures in a controlled environment. The validation of the measures and their underlying principles in this environment provides the foundation for tests of their applicability in less controlled environments.

III. METHODOLOGY

The purpose of this research was to test and measure how well a robot-operator team performs under different conditions. The robot-operator team performed navigation and reconnaissance tasks. Components of the test, described below, were the robot-operator team, the operator workstation, and the test course.

A. SYSTEM COMPONENTS

1. Robot Operators and Experimenters/Observers

Twelve people were involved in testing: a total of ten operators who were familiar with computers but who had no prior experience with remote robot operation, along with an experimenter and a backup to introduce the testing, monitor equipment, and observe performance for problems.

2. Robot-Operator Team

A team consisted of a single operator and robot. The robot was equipped for operator control using teleoperation via Ethernet or for operator control with the help of electronic navigation aids. Figure 1 shows the wheeled robot (Pioneer P3-AT Robot® by ActivMedia Robotics).[1] In teleoperation mode, it had a tilt-and-zoom color video camera, laser and sonar, and bumpers with collision-stop sensors. For navigation with electronic aids, the robot had two added features: (1) automated obstacle avoidance that allows the robot to sense and avoid 3D obstacles, and (2) waypoint navigation that allows the operator to mark a series of map coordinates for the robot to follow. The robot also had hot-swappable batteries for power and embedded microprocessors running Linux control software to manage the robot, data-logging, and feedback to the operator. Ten experienced operators each used a PC laptop, mouse, and map of the course for robot interactions.

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[1] The use of registered trademarks, companies, and brand names is for accurate descriptive purposes only and does not represent endorsement of the product by IDA or its sponsors.

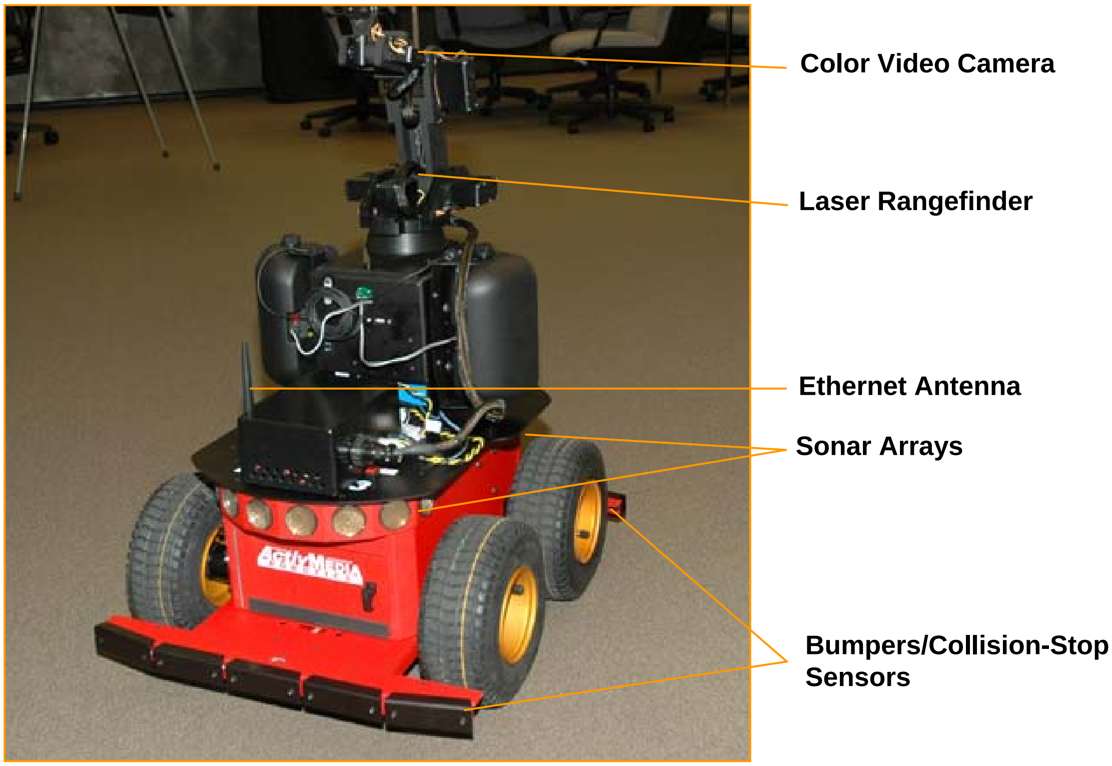

Figure 1. Pioneer P3-AT Robot®

Figure 2 shows the relationship between the software and hardware components used to control the robot. The functions of the major components are:

- Laptop PC—Operator’s workstation to control the robot and receive sensor feedback.
- Color Video Camera—Provides forward-looking video from the robot to the laptop PC.
- Video Frame Grabber—Samples the color camera’s image every 1/5 second for display on the laptop PC.
- Laser Rangefinder—Robot navigation and mapping capabilities with a range of 10–50 meters and readings every 1 degree in a 180-degree forward-looking arc.
- ActivMedia Robotic Operating System Microcontroller—Controls all low-level robot systems, including motor operation, firing the sonar, collecting sonar data, and collecting wheel encoder data.
- Saphira—An open-source software package developed by SRI that provides semi-autonomous navigation control with object-collision avoidance.
- ActivMedia Robotics Interface for Applications—Interface for intelligent robotics systems such as Saphira.

- Laptop PC Display—Information needed by the operator for robot control that is recordable for later replay.
- Log Files—Software capture of all robot state parameters and robot control inputs.

3. Operator Work Station and Test Course

The workstation consisted of a Model 5100 Inspiron Dell laptop with Windows XP connected to a Linksys-B Ethernet router. The laptop provided a control display with four information areas (Figure 3): (1) map, including robot position and activity; (2) error feedback window; (3) live-camera video; and (4) quick-reference command list showing all operator-robot inputs.

The map on the laptop's display showed the test course represented diagrammatically, but not to scale, as in Figure 4. This course was approximately 135 × 95 feet in a level-floor parking garage. The test course consisted of gates and obstacles. Pairs of 1-1/2 × 2 foot cardboard boxes formed 3D gates labeled with Roman numerals. Other free-standing boxes provided additional 3D obstacles. 2D obstacles were made by yellow-striped warning tape formed into 2-foot squares on the floor. Three pairs of paths up and back through gates were defined on the course. Each course had easier paths with fewer steep angles and fewer obstacles from one gate to the next and harder paths with steeper angles and more obstacles.

An operator controlled the robot using the laptop's keyboard and mouse. The arrow keys and space bar were for movement: go forward-backward (up-down arrows), turn left-right (left-right arrows), and space bar for stop. Camera control similarly used four keys: zoom in-out (D and A keys) and tilt up-down (W and S keys), with panning controlled by turning the robot. The mouse was used to start the robot's motors and to enter and control a semi-autonomous (aided) navigation mode where the operator established waypoints from one location to another for the robot to follow. A waypoint was deleted using the backspace key, and a waypoint inserted using the mouse and Alt key.

The well-lit work station area was about 12 feet × 12 feet. It held a second computer work station that shadowed and recorded the operator's display along with chairs for the operator and two observers. The trials were run in late fall with temperatures between 40–50 °F. Partitions made a cubicle around the workstation area that blocked the operator's view of the robot except during training when one side of the enclosure was moved.

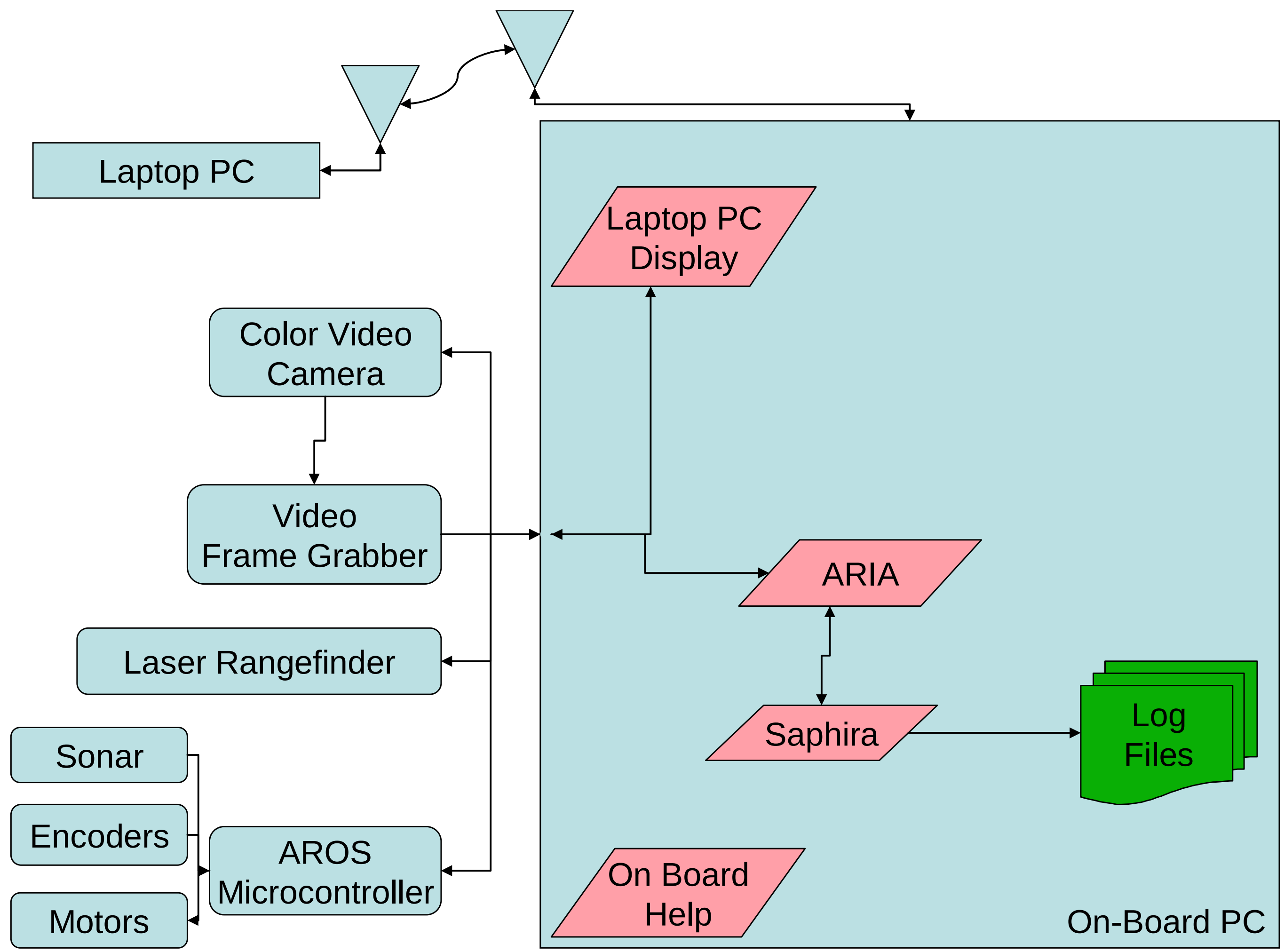

Figure 2. Schematic of Robot Control Elements

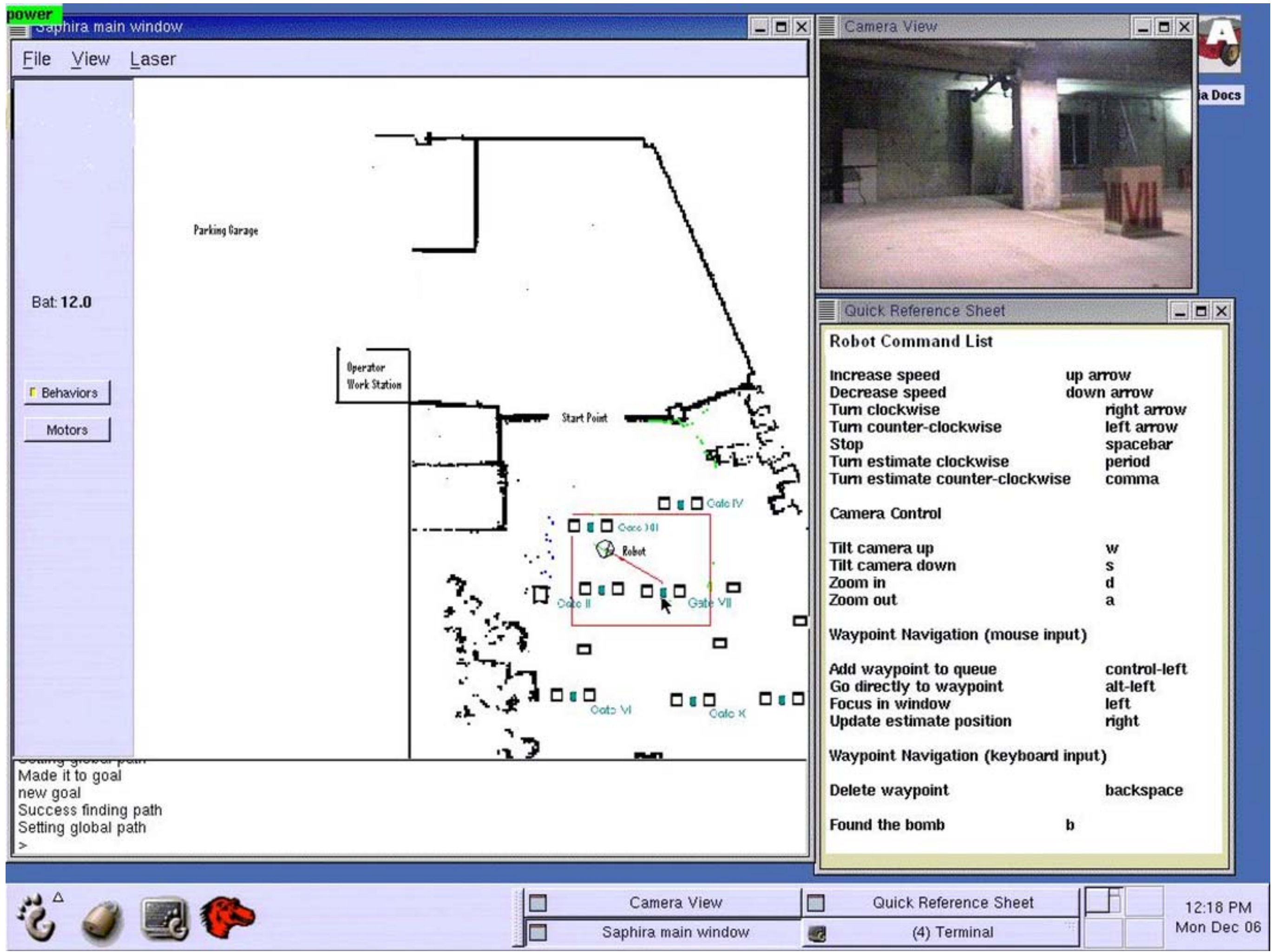

Figure 3. Laptop Control Display

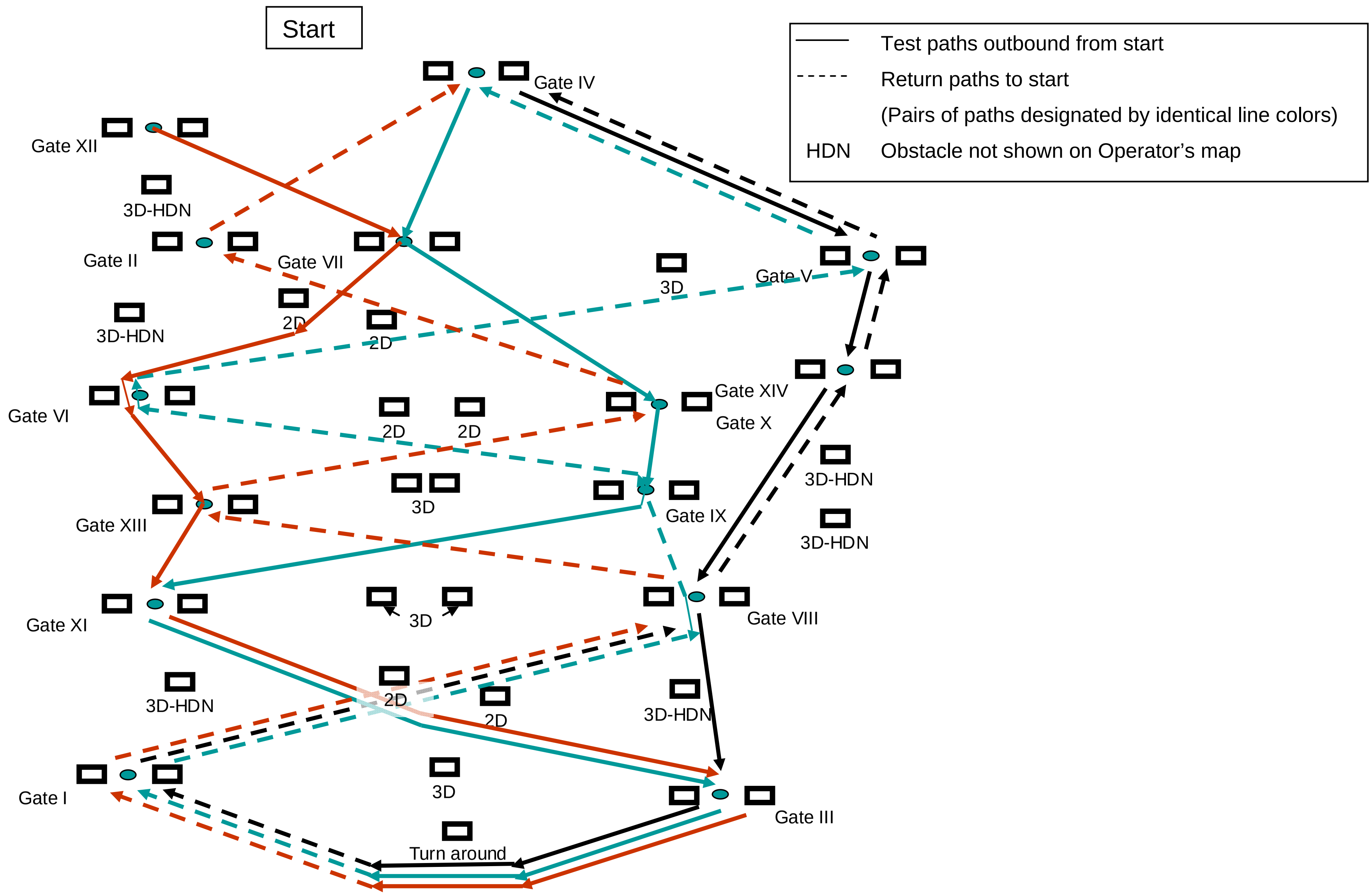

Figure 4. Schematic (not to scale) of Test Course

B. PROCEDURE

1. Mapping the Course

The robot's laser rangefinder was used to create a map of the course, including the locations of the gates and obstacles. Boxes were temporarily placed on 2D obstacles to make them detectable by the laser. An observer manually guided the robot up and back through the course while the robot's laser rangefinder scanned and mapped all obstacles. This complete map was later used for scoring performance. For the tests, however, all 2D obstacles were deleted from the map and so were some 3D obstacles. Thus, the operator (but not the robot) could see 2D obstacles with the video camera, and the robot could sense unmapped 3D obstacles with its laser and sonar, either to alert the operator or to avoid them. These mapping conditions helped distinguish robot-aided navigation from unaided navigation modes described later in this section. These conditions also mimic a real-world situation where, through teamwork, the operator and the robot each detect classes of obstacles and share information for best control.

2. Training

Before an operator arrived, the observer set up the course and workstation area, initialized the Ethernet and robot, and set the laptop's display to show the training area map. The robot was placed at a pre-established start point. An observer then showed and explained the robot and its features to the operator. The observer also showed and explained the training course and its features, but not the test course. Next, the operator was given a hard-copy map of the training course for reference, along with self-paced instructions (see Appendix A) for learning to be facile controlling the robot before starting actual tests. During training, the operator could see the training course and robot behavior but was encouraged to practice also using the computer display alone—the only information available during tests.

3. Pre-Testing

Before testing, an observer changed the operator's workstation map to the test course, changed the robot's batteries, placed it at the testing start point, and began recording the operator's display. There were two different navigation conditions—unaided and aided.

4. Unaided Navigation

Without electronic navigation, the operator performed all control via teleoperation, the most common way to operate robots today. The operator relied on a hard-copy map, an electronic map showing 3D objects (except hidden ones) and the robot's location, video images of the course, and feedback about robot movement. In addition, the laser and sonar traced all 3D objects within range on the electronic map.

5. Aided Navigation

With electronic navigation and teamwork, the robot assisted the operator in navigating a route in two ways: (1) it followed a sequence of operator-selected waypoints, and (2) it avoided 3D objects. The robot could not detect 2D obstacles, however, so the operator had to use the live video camera display to see and avoid them. During aided navigation, the operator could still go into unaided navigation mode for situations where the robot got stuck or otherwise needed help.

6. Navigation Task

An operator steered the robot through a series of numbered gates, either aided with waypoint navigation or unaided using the robot's camera and sensors. The course had several possible numbered paths marked by green circles and Roman numerals. For each test, operator-robot teams went between gates (pairs of numbered boxes) in a specific order (see Appendix B) to complete the course.

Operators each navigated the course six times. The first two paths through the test course were mostly identical and familiarized operators with navigating the course, once aided and once unaided. Four subsequent navigation paths, two up and two back, were all different. The operator navigated these paths twice with aided and twice with unaided navigation using the sequence of unaided, aided, aided, and unaided. Appendix B shows details of the test paths, conditions, and tasks.

An operator was told to move as fast as possible while avoiding 3D and 2D obstacles. At the end of a path up the course, operators were told to reverse direction by turning the robot around two boxes stacked on top of one another and following the observer's instructions about changing navigation condition (aided or unaided) and task.

7. Measurement

Two categories of measures were derived from the data: efficiency and errors. Efficiency of navigation was measured by (1) the frequency of control actions (number of key presses) per unit time and (2) the length of time between consecutive control actions. Navigation errors or accuracy was measured by counting the number of 2D obstacles an operator crossed or ran over. Error data from bumping 3D objects was not counted because in aided mode, the robot could never bump a 3D object. Thus, unaided performance was, at best, no better than aided performance. Control action measures were obtained from data logs of each type of key press and mouse click during the time it took to navigate the course. Errors were tallied manually by watching recordings of the robot's path through the course.

IV. RESULTS AND DISCUSSION

A test of aided vs. unaided navigation of robots provided support for the argument that electronic quantification of operator-robot team performance is practical. The results demonstrated the utility of a measurement system grounded in principles of teamwork, where operators and robots have defined roles, and performance derives from their integrated actions. Using team-based measurement indices, the findings showed how changes in robot technologies can affect system performance.

Data were compiled for aided and for unaided conditions across the navigation tests that each operator performed. These were summarized by calculating the arithmetic means (averages) and ranges across all operators for control actions—number of key presses per unit time as well as the times and ranges of times between key presses. Error frequency also was compiled and means calculated for the number of obstacles operators failed to avoid. Tests of significance were not done due to the small number of operators and data.

Overall results showed that compared with unaided navigation, aided navigation had fewer control actions, more free time (intervals of greater than 5 seconds between control actions), but a higher number of errors. Table 2 gives these three measures across the two conditions of aided and unaided performance. Although the metrics are different, the comparisons of results grouped by condition are instructive.

Table 2. Mean Number and Mean Time for Response Parameters

Navigation	Number of Key Presses	Free Time / Navigation	Number of Errors
Aided	12	7.8 s	>1
Unaided	50	1.6 s	<1

The mean number of key presses per unit time for aided vs. unaided navigation was 12 vs. 50. In addition, mean (free) time between key presses was 7.8 seconds for aided navigation, ranging from 1.8 to 20.7 seconds; for unaided navigation, mean time between key presses was only 1.6 seconds, ranging from 0.5 to 3.2 seconds. The mean number of errors for aided navigation was greater than one while unaided navigation resulted in less than one error per run.

The time intervals between key presses were further analyzed by summing them by length: all 0.1-second intervals plus all 0.2-second intervals, and so on. The accumulated percent number of key press intervals (*y* axis) was then plotted as a function of the time interval (*x* axis) an operator paused between key presses. Figure 5 shows both aided and unaided navigation data for four representative operators.

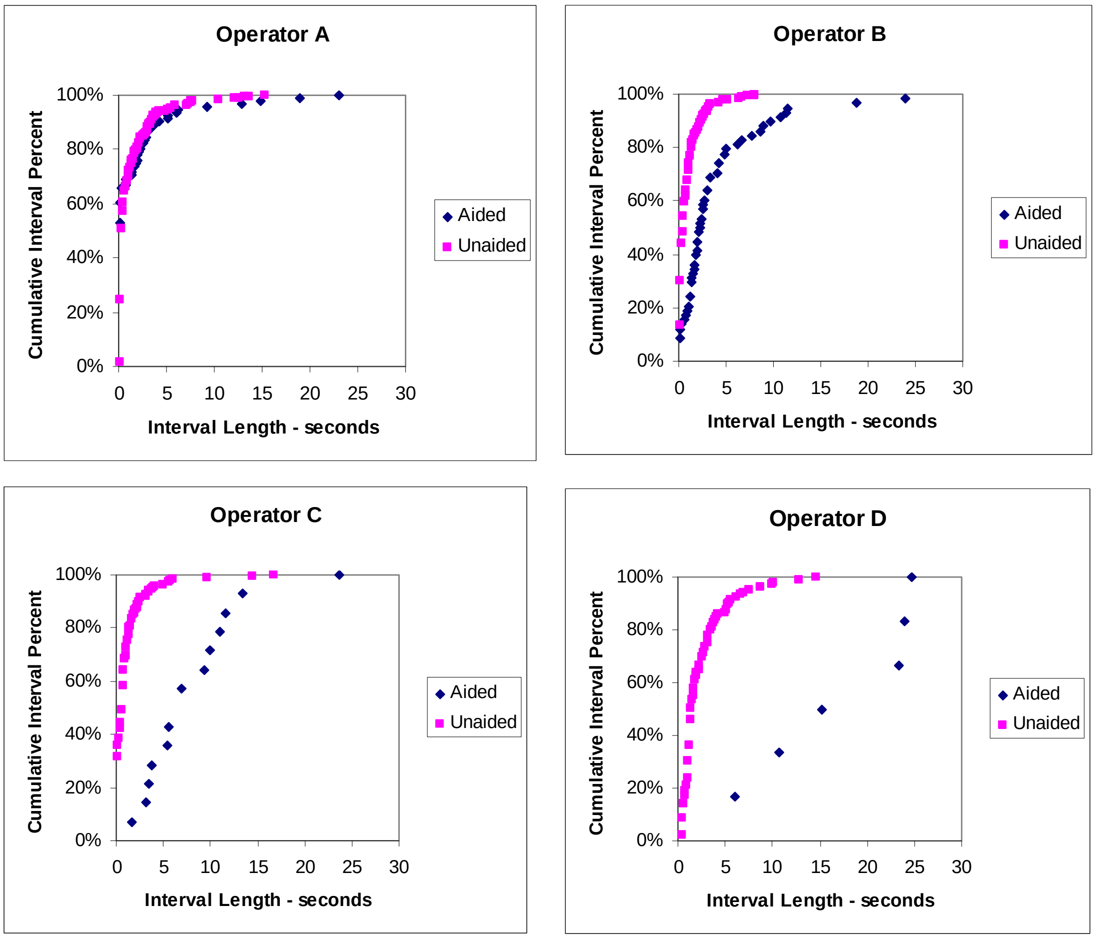

Figure 5. Key Presses as a Function of Time Intervals Between Key Presses

A striking characteristic of the data for time between key presses is the shapes of the distributions. For the unaided mode, 90% of those data are less than 5 seconds. This was the case regardless of a test run's length, which varied considerably among operators. For aided navigation, on the other hand, only 10% to 80% of time interval distributions between key presses were less than 5 seconds.

These plots show that operator-robot teams using the aided navigation mode can exercise more intermittent control with fewer key presses and more time between them than in unaided navigation. This means they have more "free time" to consider navigation

strategy and route planning. In contrast, in the unaided navigation mode, operators had less time between inputs for these functions due to a nearly continuous requirement to monitor and react to robot feedback.

Perhaps the most interesting result from these plots of time intervals between key presses is their variation in the aided mode (Figure 5). Sample results from individual operators using aided navigation or capitalizing on the robot's initiative to follow a path defined by waypoints and to avoid obstacles followed different strategies. At one extreme was the monitoring strategy of nibbling at the course (Figure 6, Operator A) with planning gaps in between a sequence of nibbles. This represented a small difference in performance from the unaided mode on this metric. At the other extreme was parsimony—long planning intervals with few navigation corrections and a higher risk of making errors (Operator D). For this operator, in the unaided mode, 90% of the distribution of time between key presses was 5 seconds or less, while in the unaided mode only 20% was in this range. Intermediate strategies in which nibbling and parsimony were alternated also occurred (Operators B and C). In all cases, aided navigation resulted in more "free time" than unaided navigation. Why one strategy was adopted over another is not known, but reasons could include trust or lack thereof in autonomy or simply a desire to exert more control in the situation. In addition to following a path, operators had to monitor for 2D obstacles, unseen by the robot, and respond to navigation problems beyond the robot's capabilities. The errors made by crossing or overlapping 2D obstacles were slightly higher for aided navigation, suggesting that operators were less vigilant in this mode. Such errors were the one negative attribute of using aided navigation.

Overall, aided and unaided navigation represent a continuum of robot-operator teamwork interaction that ranged from little to no interaction (autonomous) to constant interaction (teleoperation). Unaided robot navigation is a full-time job that places high demands on operator attention; aided robot navigation demands less constant attention from the operator. Less operator attention and interaction with the robot generally seems to equate to more errors, suggesting that operator vigilance needs emphasis or that the navigation technology needs enhancement for improved performance.

Operators said that unaided navigation gives the operator the sense of being in control. In contrast, aided navigation was said to be good for "open spaces" but not for detailed control situations. Although operators could make the robot move identically in either mode, that is not what they did. When discriminating robot movements were needed, operators dropped out of aided navigation in favor of unaided control.

V. CONCLUSION

The test demonstrated the usefulness of evaluating robot-operator teams to assess success and failure factors in the performance of robots and the effects of different technologies on that performance. The results of measuring robot-operator performance can give designers and program managers insight into the factors affecting job performance and mission success. The initial results reported here may not generalize across different robot-operator teams and tasks; however, the measurement approach should generalize across platforms and technologies.

VI. RECOMMENDATIONS

The measurement concept developed and tested as a proof of principle would benefit from additional assessment and enhancements before transition to the user community. The current work with one type of robot and limited data needs expansion to show that the concept generalizes. The next steps should be to extend the measurement approach to more complex robot-operator tasks with the goal of providing quantified answers to which technologies will help robot-operator teams better accomplish their jobs. Additional tests should include data logs and metrics for other ground robots and for air robots. To make implementation easy, the schema and instrumentation for data collection need to be relatively compatible with different onboard computers, data-logging systems, and user interfaces and control stations of various robots. The most effective way for that to happen is for contractors and developers to integrate the evaluation methodology into their robot systems and planning for employment under more realistic conditions than in the current study.

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APPENDIX A—INSTRUCTIONS FOR PARTICIPANTS IN PROOF–OF–PRINCIPLE TESTS

A. Overview

Today, you'll help us understand how to measure human-robot teamwork. The first task is learning and practicing how to operate the robot. Then, there will be a series of tests where you navigate the robot through a course, followed by searching for a simulated bomb. The course is level terrain in a garage with boxes and floor markings to simulate obstacles. Sometimes the tests are with navigation assistance from the robot (aided mode) and sometimes with only the robot's sensors (unaided mode).

You can see the robot while learning how to operate it. But for the tests, you'll see only a control display. So, *practice using the control display* as much as possible, even during learning.

B. Purpose

The purpose of the tests is to find out if we can measure how well you and a robot perform as a team. You give commands from a computer terminal that causes the robot to perform navigation, search, and find tasks.

1. Learning and Practice

Meet the Robot. Ask the Observer for an introduction to the robot's features. The start point for training is in the area you see in front of the control station.

2. Unaided Navigation Using Robot's Sensors

Control Display. Look at the robot's control display and its four information windows:

(1) map (left) including robot position and activity

(2) feedback window (below the map)

(3) live camera video (top right)

(4) command list (lower right)

Do the following to learn about the control display.

1. *Control*. Put the cursor on the map window and left click the mouse.
2. *Camera.* Zoom in with the robot's color TV camera (D key) and then zoom out again (A key). Separately press each key a few times until you end up at the position where the display no longer changes. Next, tilt the camera up (W key) and then look down (S key). Return it to looking ahead.
3. *Turns.* Use the mouse cursor to highlight and click on the MOTORS button (left screen) to start the robot's motors. Next, left click on the map window.
    a. Locate the robot symbol (black octagon stop-sign shape on the map and notice the extra black line marking the front of the robot.
    b. Turn to the left by pressing the left arrow key three times. Each key press is about 10 degrees counterclockwise. The robot is a bit slow to respond, but notice the red rectangle and purple arrow combination as the robot turns. The red rectangle shows the robot's expected heading and the purple arrowhead its current heading. The long green arrow is the current estimate of where the robot is pointed; it updates slowly.
    c. Turn back toward the right (right arrow key) using two key presses. Note that pressing the left-left-left-right-right commands produce a net 10-degree turn counterclockwise.

Stop the robot (space bar).

Next, turn and stop the robot a few times for practice.

4. *Forward-Backward Movement.*
    a. Move the robot forward (up arrow) and then stop (space bar).
    b. Move the robot forward and look at the map display to see the movement.
    c. Stop the robot.
    d. Press the up arrow key twice to make the robot move at its highest speed.
    e. Slow the robot (down arrow) with one key press and stop with two key presses.
    f. Press the down arrow key again to put the robot in reverse and then stop.

Note: The up arrow tells the robot to go forward, and there are two forward speeds. The down arrow tells the robot to reverse its direction, and there is only one speed. You can slow or stop the robot whether going forward or in reverse by using the arrows. The space bar stops the robot no matter what it's doing.

5. *Maneuver.*

   a. Drive the robot toward the green circle marked as “Gate I” on the map. A cardboard box on either side of the green circle makes the gate.

   b. Bump a box on one side of Gate 1 with the robot so the robot crashes and stops.

   c. Look at the robot symbol on the map and the message in the feedback window (below the map) showing the robot is stopped and stuck.

   d. To continue, back up the robot. Then, stop either with the up arrow key or the space bar.

   e. Notice the green dots (laser range finder) and blue dots (sonar reflections) that outline what objects these sensors are detecting. Clear space between the robot and a dot means that no object is there. Sonar sees close to the robot’s back and front. The laser sees farther forward but not behind. The black squares show known and established walls and other objects. Note that you’ll come upon unmapped objects, too (that can only be seen with the robot’s camera).

   f. Next, maneuver the robot and go through Gate I and stop.

   g. Continue by maneuvering the robot through Gates II, III, and IV—but avoid hitting boxes at the gates, boxes that are obstacles on the course, and 2D black-and-yellow squares on the floor (that you can find only with the camera).

   h. Practice until you are comfortable with how the robot turns and responds to your commands and how the display shows what’s going on. Make sure to practice around gates and obstacles to learn how best to turn the robot.

3. Aided Navigation Using Waypoints

In the aided test, the robot helps you navigate a route using points along the way you want to go (waypoints) that you select with the mouse cursor. *Waypoints are a feature in addition to all other control features.*

Do the following to learn about using waypoints.

1. *Start Waypoint Mode*. Turn on BEHAVIORS (left button mouse click) to start the waypoint mode. (The marker in the left display window changes from gray to yellow, and the robot now will move before, during, or after you select one or more waypoints.) After clicking on BEHAVIORS, you must left mouse click on the map so that the robot will accept the command.

2. *Mark a Waypoint.* Decide on a waypoint and mark it with the mouse cursor (Ctrl + left mouse button). Notice the green square on your display that marks that waypoint.

3. *Maneuver with Waypoints.* Next, mark many waypoints to navigate through the gates without hitting 3D obstacles (boxes) and without crossing 2D obstacles (yellow-striped squares). Notice that red dots mark waypoints after the current (green) one on your display.

4. *Change waypoints.* Erase a waypoint (backspace) and then plot new waypoints. That's one way to change a route.

5. *Insert New Waypoints.* Use the mouse cursor to insert a waypoint in between those already (Alt + left mouse button). Notice how this insert command differs from what you did earlier to mark one waypoint after another. That's another way to change a route.

6. *Waypoint Errors.* Force an error by placing a waypoint so the robot will hit a box.

    a. After the robot stops, turn off BEHAVIORS on the display (left button mouse click) so you're in non-aided mode. Manually move the robot away from the box.

    b. Then, enter waypoints with the mouse, turning on BEHAVIORS whenever you're ready for robot movement.

7. Practice adding waypoints (and editing them) by navigating through Gates I, II, III, and IV and avoiding obstacles around the training area. Continue until comfortable.

4. Failed Waypoint Navigation

8. *Waypoint Confusion.* Sometimes the robot can't find a path to the next waypoint (even if there is one).

    a. Ask the Observer to put an obstacle on the training course to cause the problem.

    b. Select the new waypoint and observe what happens. Also, notice the message on your feedback window.

Note: The waypoint planner fails when it doesn't sense a large enough space for the robot to navigate. Turn off BEHAVIORS mode and navigate manually to a different location. Turn on BEHAVIORS again and try new waypoints.

5. Begin Testing Session

The test is to navigate.

1. *Testing Start Point.* Ask the Observer to move the robot to the testing start point and reset the computer while you take a short break.

2. *Navigate Task.* The navigate task is to drive the robot through a series of numbered gates either aided with waypoint navigation or unaided using the robot's camera and sensors. The course has several possible numbered paths. Notice how a hard copy of the map has navigation reference points marked by green circles and roman numerals. For each test, you pass the reference points in the order shown and go between gates (pairs of numbered boxes/obstacles) to complete the course.

Signal your find (B key for bomb) on the computer and tell the Observer when you're done.

3. *Tasks.* The Observer will tell you which gates to go through, either aided or unaided, after you're done reading these instructions. Note that in the aided mode, all controls for unaided operation still work. Your navigation task is to move as fast as you can while avoiding 3D obstacles (boxes) and 2D obstacles marked on the floor by yellow-and-black squares. Some obstacles appear on the map but there also are unmapped obstacles. There's a turnaround point marked by two stacked boxes at the far end of the course.

4. *Reminders.* Get your first test course assignment and make sure you know if the task is aided (waypoint navigation) or unaided (sensor navigation). Use the robot's sensors to best advantage to avoid known and unknown, 2D and 3D obstacles. Speed is urgent in finding the mock bomb!

Use waypoint commands whenever available.

5. *Questions?* When you're ready, proceed to the next page for course navigation information.

APPENDIX B—TEST PATHS AND TASKS

A. Navigate the Robot Course Using the Following Order

A	IV	V	XIV	VIII	III		(up - unaided)	Practice runs
B	I	VIII	XIV	V	IV		(back - aided)	
E	IV	VII	X	IX	XI	III	(up - unaided)	
D	I	VIII	IX	VI	V	IV	(back - aided)	
C	XII	VII	VI	VIII	XI	III	(up - aided)	
F	I	VIII	XIII	X	II	IV	(back – unaided)	

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14. ABSTRACT

Assessments of small air and ground robot systems often focus on how well the equipment functions. This document outlines a research schema for measuring robot-operator team performance and presents an initial proof-of-principle test for quantitatively assessing that performance. The research defined performance factors associated with moving a small robot from point A to B, and quantified the effects that different sensor and navigation technologies have on that performance. Results provided support for doing electronic quantification of operator-robot team performance. Results also showed how changes in robot technologies can impact system performance. The design of the research was as non-task and non-platform specific as possible to facilitate generalization.

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